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Identification of Excess Heat Utilisation Potential using GIS: Analysis of Case Studies for Denmark

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Abstract:

Excess heat is present in many sectors, such as the industry and utility. The utilization of these heat sources could reduce the primary energy consumption and thus reduce carbon dioxide emissions. This work presents the results of a geographical mapping of excess heat, in which excess heat from the industry and utility sector is distributed to specific geographical locations in Denmark. Based on this mapping, a systematic approach for identifying cases for the utilization of excess heat is proposed, considering district heating, process heat and power generation. The technical and economic feasibility of using this approach is evaluated for four scenarios. Special focus is placed on the challenges for the connection of excess heat sources to heat consumers, as well as tax schemes applicable in Denmark. To account for uncertainties in the model input, Monte Carlo simulations and Morris Screenings are performed to determine the standard deviation of the results and to determine the most important model parameters. The presented method shows how the geographical mapping of excess heat sources can be used to identify its utilization potentials. In combination with the economic model, a fast evaluation and comparison of the feasibility of different matches can be performed. The evaluation of the identified case studies shows that it is economically feasible to connect the heat source to the public energy network or use the heat to generate electricity. However, the uncertainty analysis suggests that the results can only be indicative and are useful for a fast evaluation and comparison of different matches.

Keywords:

Excess heat, Heat recovery, GIS, Industry, Utility, District heating, Power generation, Energy Efficiency.

1. Introduction

Excess heat is available from many sources and its avoidance or utilization would reduce the primary energy consumption and carbon dioxide emissions associated with the burning of fossil fuels. The full recovery of excess heat is connected to several challenges: (i) lack of information exchange between excess heat producers and potential excess heat users, (ii) technical recovery potential and (iii) economic and governmental frameworks. To overcome these challenges a fast and comprehensive method for identifying utilization potentials of excess heat and evaluating their technical and economic feasibility is required. Such a method would allow energy planners to find synergies between emitters of excess heat and heat demands on a regional level and quickly assess specific cases, before performing detailed analyses.

As it is clear from the following references, the literature has so far focused on quantifying excess heat and their temperature levels, as well as analysing potentials for their utilisation. Several studies quantified the industrial excess heat, such as Miro et al. [1] for waste heat originating from different countries and regions and Naegler et al. [2] on an European level. These works provide useful information for further analyses about excess heat. Methods used to estimate the waste heat potential of regions, were reviewed by Brückner et al. [3]. The considered methods and literature used in this study are categorised into two categories, namely surveys and estimates. The geographical locations of the heat sources are not specifically taken into account, however size parameters for companies (e.g. number of employees) are used in the classification for the estimation of the excess heat. Brückner et al. [4] further investigate the utilisation of waste heat for residential heating in an urban neighbourhood in Germany and performs an economic analysis of heat transformation technologies for industrial waste heat [5]. For Sweden, Broberg et al. [6] estimate the potential of industrial excess heat for Swedish district heating networks and show based on cost calculations how excess heat investments become profitable. Broberg and Johansson [7] further review the technologies for the utilization of excess heat and estimate their potential for a region in Sweden.

An analysis by Hammond and Norman [8] shows the heat recovery opportunities in the UK industry from 11 industrial sectors. The utilisation potential for different technologies is found considering the waste heat temperature. An analysis for heat transportation between sites with surplus heat and heating demand is further performed. Another study for the UK [9] investigates the potential of using industrial excess heat for district heating. The potential, limited by transmission distances, found that approximately one third of the UK excess heat could be used in district heating networks. A study performed by McKenna and Norman [10], presents a spatial model of industrial heat loads and technical recovery potential in the UK is presented. This study analyses heat loads and wastage, grouping them in different temperature bands and estimating the recovery potential.

Persson et al. [11] show how heat synergy regions can be identified in Europe, using carbon dioxide emission data. Excess heat from fuel burning processes is mapped on a European scale and is compared to the new European heat atlas. Lund and Persson [12] further analyse the Danish potential of low temperature heat sources for the use in district heating networks by heat pumping. Their work considers besides low temperature industrial excess heat and supermarket refrigerators, natural sources such as ground water and lakes. Based on this analysis a clear potential for the utilisation of low temperature heat in Denmark can be identified, justifying more detailed and precise analyses of excess heat sources and how they can be integrated with the existing energy system.

The aim of the current work is to apply Geographical Information Systems (GIS) based data on excess heat and heating demand to identify and evaluate the feasibility of relevant cases for the utilisation of excess heat. The evaluation of the feasibility is based on technical practicability as well as economic indicators for each case.

The approach and method for identifying potential synergy cases and the background of the data is first described in detail. Based on exemplary identified syneriges with GIS, four cases for the utilisation of the excess heat were analysed. This analysis included (i) technical considerations, such as the time profiles of heat sources and sinks, the available and required temperature levels, (ii) economic considerations for the investment in new equipment and its operation, (iii) governmental frameworks (e.g. taxes, subsidies) and (iv) environmental considerations, such as the type of replaced heating sources and alternative options. Eventually an uncertainty analysis of the models was conducted to determine the confidence of the result and a sensitivity analysis was used to determine the most important input parameters to allow an optimised application of the model.

2. Methodology

2.1. Geographical Mapping and Identification of Synergies

This work originates in an earlier study [13] where industrial excess heat, also referred to as waste heat, from thermal processes is determined for industrial production sites in Denmark. Temperature levels for each of the considered industrial processes are determined [14] and assigned to the individual sites. The work show the potential of using industrial excess heat in Denmark for district heating. In the current analysis an identical distribution key was used to allocate the total industrial excess heat, as it is found in [15] for individual production sites. In addition, excess heat from the utility sector (power and waste water treatment plants) was included, for which the excess heat is distributed by the plant capacities [16,17]. District heating areas [18] and their heating demand, as well as fuel types were integrated into this work. All the above data were treated and analysed using QGIS [19], an open source Geographic Information System (GIS), with map material from OpenStreetMap OSM [20].

In this analysis, the utilisation of excess heat for heating of buildings or industrial processes, as well as the generation of electricity, was considered. To identify specific cases where the use of excess heat was feasible, the evaluation of the technical and economic feasibility of these cases was performed as follows:

1. Evaluation of the theoretical potential of district heat substitution by excess heat in Denmark, as performed in [13]
2. Identification of district heating areas with substitution potential and analysis of the origin of excess heat in GIS
3. Assessment of the sources with the highest potential: Sector of the match and company, typical excess heat amount and temperatures for processes of the sector and determination of the distance to the nearest heating area. For each heat sink, only the heat source with the best feasibility was considered.
4. Economic and technical evaluation of the case: This requires the estimation of typical operating hours and profiles, as well as determination of current heating prices

In case of synergy between two industrial complexes, the replacement of process heat with excess heat was considered in a similar manner. Instead of step 2, clusters of excess heat were identified. Such clusters indicate the presence of several companies in the industry and utility sector. From the excess heat and process temperatures of individual sites, matches could be found.

The evaluation of cases for electricity production were found by identifying industrial sites which either have (i) high temperature excess heat (> 150 °C) from other sources than boilers or (ii) are in isolated locations.

The technical and economic evaluations of the matches were performed as described in section 2.2 and 2.3, with the aim of obtaining an indication of the feasibility which justifies further analyses. To perform the feasibility evaluation the following characteristics were required: the temperature, the amount and the classification of the industrial sector, as well as the temperatures, capacity and type of the heat sink. This information was included in the GIS model for each site on a sectorial level, however further refining of the data was required for the individual process by using information from the literature.

2.2. Utilisation of excess heat

The utilisation pathways for the use of excess heat, considered in this work are shown in Fig. 1. Three technologies were considered, namely direct heat transfer, heat pumping and Organic Rankine Cycles (ORC). The considered heat sinks were: industrial sites requiring process heat, heating demand of buildings and the electrical gird.

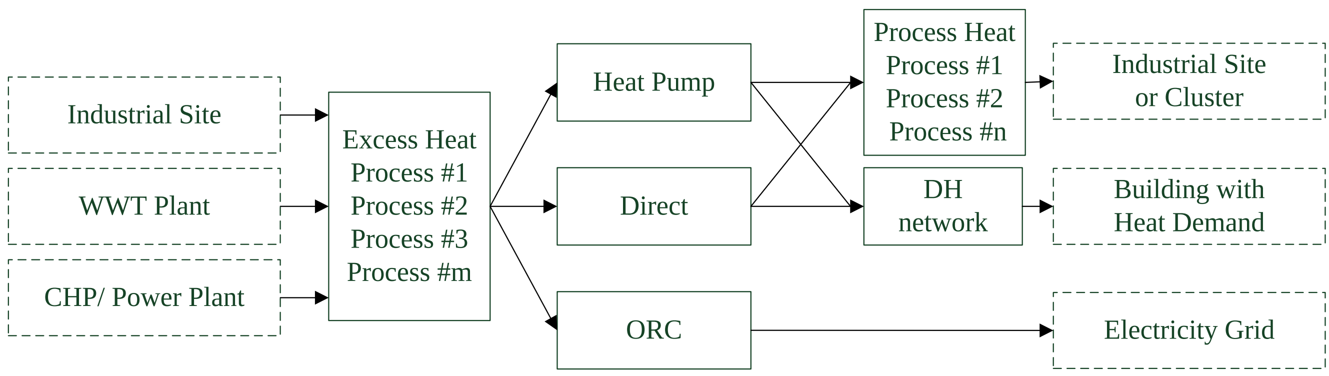

Fig. 1. Utilisation pathways for excess heat from different sources.

The direct utilisation of the excess heat is possible when source temperature is, by the minimum temperature difference, higher than the required supply temperature of the heat sink. In the case of district heating, it was assumed that the excess heat was transferred to the district heating network via one heat exchanger. In the case of process heat, a transfer loop between the two sites was considered a requirement and thus presents the need for a second heat exchanger on the sink site.

A heat pump is required when the temperature of the excess heat T_{EH}, after the subtraction of the minimum temperature ΔT, is equal or below the required supply temperature T_S. Some part of the heat could be transferred directly in some cases, as shown in the works by Jensen et al. [21] and Ommen et al. [22], however in this work all the heat is assumed to pass the heat pump. The heat pump is modelled using the Carnot efficiency and is corrected by a factor η to obtain the real Coefficient of Performance COP [8].

$$\mathrm{COP} = \eta\ \mathrm{COP}_{\mathrm{carnot}} = \eta\ \left(\frac{T_S\ +\ \Delta T}{(T_S\ +\ \Delta T) - (T_{\mathrm{EH}} - \ \Delta T)}\right) \tag{1}$$

The third option is to use an ORC to produce power from the excess heat in cases where no suitable heat sink is present or if the temperature of the excess heat is high and power is seen as the favourable option. In those cases, the electrical efficiency of the ORC depends amongst other on the excess heat temperature. In this work, the efficiency of the ORC is found using equation (2) assuming an electrical efficiency between 30 % and 50 % within a temperature range of 100 °C to 350 °C of the source applied to the Carnot efficiency. The choice of the electrical efficiency is based on literature correlations [7,8,23] and T_0 is set to the environmental state at 25 °C.

$$\eta_{\mathrm{ORC}} = \eta_{\mathrm{el}} \left(1 - \frac{T_0}{T_{\mathrm{EH}}}\right) \tag{2}$$

The minimum temperature differences considered in this work were 5 K for streams below 60 °C, which are assumed to be liquid and originating from e.g. condensate or compressor cooling. For streams above 60 °C, a value of 10 K was used, accounting for the mainly high temperature exhaust gas flows.

2.3. Excess heat and heating demand

The excess heat sources, as well as the heating demand, are often not constant over time. It was thus necessary to account for their operating profile in relation to each other. In this work, seasonal profiles were used to correct the possible utilisation of excess heat towards different source and sink profiles. The profiles allocate the heat demand and supply over four periods of the year. Two profiles were created for district heating and four profiles were considered for the industry and utility plants. The representative profiles take into account that some industries have a constant production (e.g. chemical and food industry) and some have a higher production during warm periods or vice versa (e.g. building materials). The first district heating profile follows the annual residential heating demand. To account for situations where the summer heating demands are covered by waste incineration plants, and thus no additional heat can be absorbed by the system, a second district heating profile was created.

Table 1. Distribution profiles for the district heating (DH) demand and excess heat from process (P) over one year in percent.

	DH1 [%]	**DH2** [%]	**P1** [%]	**P2** [%]	**P3** [%]	**P4** [%]
Q1	40	50	25	20	10	30
Q2	15	5	25	30	40	20
Q3	10	0	25	30	40	20
Q4	35	45	25	20	10	30

Another factor which was critical for the determination of the particular sizes of equipment as well as feasibility was the annual operating hours of a source or sink. If the excess heat is emitted in relatively small periods of time, the power will be higher and require larger components. To account for variations of the operating hours, a selection was made based on the number of working shifts at the site. Typical operation profiles allow for three shifts, which was translated into 3000, 5000 or 7000 operating hours a year. There are also daily variations of the sink and source, however it was assumed that these variations can be neglected as storage tanks of reasonable sizes could be implemented and act as buffers between supply and demand.

2.4. Economic evaluation

The economic evaluation of each case study was performed by determining the economic feasibility, based on the Total Capital Investment (TCI) and the Operation & Maintenance (O&M) costs. The framework for investment was accounted for by including, amongst other, inflation, interest rates and increases in fuel price. Investment and operating costs are presented in section 2.4.1. A separate focus of the economic analysis was the inclusion of taxes and subsidies in Denmark and how they influence the feasibility of the project. An elaboration of this aspect is further presented in section 2.4.2.

2.4.1. Investment and operating costs

The considered investment costs for utilising the excess heat in this work consist of the piping between heat source and sink, heat exchangers and heat pumps, as well as investments in equipment for an ORC if electricity is to be produced. Investment and maintenance costs were found using the Danish Technology Catalogue [24] and for piping the summary by Nielsen and Müller [25]. The lifetime of the purchased equipment considered for the economic analysis was chosen to be equal in all cases.

Table 2. Summary of the main model parameters and their distribution in the input uncertainty space for the evaluation of the case studies. (Uniform U[lower;upper]; Normal N[μ;σ]; Gamma G[a;b])

Item	Value	Unit	Uncertainty	Source
Net Grid Electricity	40.5	[€ MWh^{-1}]	N[40;2.5]	[27]
Electricity cost Increase	2.0	[% p.a.]	U[1;3]	[27]
DH Substitution Price	38.9	[€ MWh^{-1}]	-	[28]
Equipment Lifetime	20	[years]	G[2;2]	[24,29]
Inflation	2	[% p.a.]	-	[27]
Interest Rate Debt	10	[% p.a.]	U[8;12]	[5]
Loan Duration	5	[years]	-	[5]
Value Energy Saving	0.055	[€ kWh^{-1}]	U[0.05;0.06]	-
DH Pipe TCI	$f(Q_{DH})$	[€ kW^{-1}]	U[-30%;30%]	[25]
HP TCI	680	[€ kW_{heat}^{-1}]	U[550;800]	[29]
HP O&M	5.5	[€ kW_{heat}^{-1} $year^{-1}$]	U[5.0;7.0]	[29]
HEX TCI 1	60	[€ kW_{heat}^{-1}]	U[50;100]	[29]
HEX O&M	2	[€ kW_{heat}^{-1} $year^{-1}$]	U[1.5;3]	[29]
ORC TCI	1600	[€ kW_{elec}^{-1}]	U[1400;2000]	[23,30]
ORC O&M	35	[€ kW_{elec}^{-1} $year^{-1}$]	U[30;40]	[23]
HP Efficiency	0.55	[-]	U[0.5;0.6]	[8]
ORC Efficiency ratio	0.35	[-]	U[0.3;0.4]	[7,8,23]
ΔT_{min} (> 60°C)	10	[°C]	U[8;12]	-
ΔT_{min} (< 60°C)	5	[°C]	U[3;7]	-

Fuel prices, in particular the district heating prices, were found for each heating area in the price statistics of the Danish Energy Regulatory Authority [26] which are used to correct the overall substitution given in Table 2. It is further assumed that the excess heat is available at no cost if the investment is performed by the source owner (e.g. the factory). The revenues for selling excess heat as district heat are chosen to be equal to the average heating price in the connected heating area.

2.4.2. Taxes and Subsidies

Danish taxes on energy were introduced after the oil crises in the 1973, which aimed at reducing the consumption and to increase the security of supply. A tax on carbon dioxide was introduced in 1992 to reduce fossil fuel use and their harmful environmental effects. In 2005 this CO_2 tax was followed by the European carbon emission trading scheme. The payable taxes and possible tax shields can vary considerably based on the excess heat source and utilisation technology. For each of the considered pathways a brief overview is given for the Danish legislation [31,32].

Table 3. Overview of the taxability of the utilisation of excess heat based on the source and sink.

Source / **Sink**	Process	Utility system	Ventilation (room heating)	Waste water (process)	Waste water (other)
Room heating	Tax	Tax	No Tax	Tax	No Tax
Hot water	Tax	Tax	No Tax	Tax	No Tax
Cleaning (CIP)	No Tax	No Tax	No Tax	No Tax	No Tax
Process	No Tax	No Tax	No Tax	No Tax	No Tax
Electricity	No Tax[1]	No Tax[1]	No Tax[1]	No Tax[1]	No Tax[1]

[1] No tax for electricity generation, but tax for electricity use if the source is not renewable as e.g. biogas

Danish companies are generally obliged to pay a tax on utilised excess heat when the heat comes from a process and is used by a special installation for a non-process purpose. The tax on surplus heat can originate in the legislation, regulating the taxation of energy for process and non-process purposes. The aim of the Danish surplus heat tax is to secure that no speculation is made in order to avoid paying similar energy tax for similar energy uses. The tax on surplus heat is put in place to compensate for a missing tax payment when process waste heat subsequently is used for a higher tax category as e.g. space heating.

With respect to the chosen cases in this work the sources are from process heat, utility systems and waste water (other). The source is further utilised for room heating, process heating and electricity generation. Furthermore only the case of external utilization was considered, excluding the possibility of regenerating the excess heat for the use on the site. From Table 3 the most relevant, taxable, cases are excess heat from processes for room heating and electricity generation, highlighted in grey.

(i) Process heat for district heating (directly or via heat pump). If the excess heat is sold to a district heating company and the temperature level allows a direct heat transfer, the payable tax is the difference of the room heating tax (6.75 € MWh^{-1}) and the process heat tax but not more than 33 % of the excess heat price paid by the district heating company. Furthermore, a tax reduction is obtainable when a heat pump is used. The taxable heat is then reduced to the difference of the excess heat and twice the electricity needed, meaning only the heat produced at the COP above 3 is taxed.

If the excess heat is sold to a district heating company and a heat pump is required, the amount of taxable sold heat is reduced by the electricity used multiplied by a factor of three. However the electricity used by the heat pump is taxed at the rate of electricity used for room heating. This adds the Public Service Obligation, electricity tax for room heating and the fee for the TSO to the net electricity price, resulting in a unit price of 139 € MWh^{-1}.

(ii) Electricity generated from excess heat. The electricity generated from excess heat has no energy tax, as it currently is for all fuels. There are environmental taxes (e.g. NOx and SOx) for burning of fuels though. Taxes only occur for the use of electricity and if the electricity is generated using renewable sources, tax credits of up to 20 € MWh^{-1} can be applicable.

For the consideration of national subsides, the sale of energy savings to utility companies was included where relevant. The obligation for energy savings for utility companies allows, for example industries, to sell their energy saving projects. Based on market prices, the value of one MWh saved energy was chosen to be 54 €. This price depends on supply and demand, the utility company it is sold to, and at which time of the year the energy savings are offered on the market, thus resulting in an uncertainty, which was estimated to be ± 15 %.

2.4.3. Economic Comparison

The economic evaluation was performed by first calculating the average unit price of heat or electricity produced over the lifetime compared with the local energy prices. This includes the TCI, O&M, the annuities, eventual subsidies and the energy (heat or electricity) recovered from the excess heat.

$$\text{Unit Cost}\left[\frac{€}{MWh}\right] = \frac{(\text{TCI} + \text{Annuities} + \text{O\&M} - \text{Subsidy})}{\text{Energy } \times \text{Lifetime}} \tag{3}$$

A second criterion for the comparison was used by determining the maximum acceptable investment costs for a given system [5]. This approach is independent of cost estimations for the equipment, subsidies and taxes, as it only requires the energy prices as well as economic investment conditions.

$$\text{Acceptable Investment } \left[\frac{€}{\text{kW}}\right] = \text{Operating hours } \times \Delta\text{Unit Costs } \times \frac{1}{\text{AF}} \tag{4}$$

The acceptable maximum investment costs was found by the differences ΔUnit Costs of the current prices for the supply and at which the new system would supply the heat or electricity. Furthermore, the annual operating hours and the annuity factor AF, as a function of the interest rate and loan payback time, was used.

At the end a private economic investment calculation was performed from the viewpoint of the owner of the industrial excess heat source. Here the revenue for the sold heat was found as half of the difference from the unit costs and substitution price. The share of the revenue will depend on negotiations between the excess heat owner and heat consumer. For electricity generation the net electricity price was used. Based on this, the Net Present Value (NPV) and Internal Rate of Return (IRR) were found for a discount rate of 5 %.

2.5. Uncertainty and Sensitivity Analysis

To quantify the uncertainty of the model output, the Monte Carlo (MC) method was used [33]. With this method the probability of the model output was determined, considering the uncertainty of inputs. With the MC method, the model was evaluated several times, using random input values generated within the input uncertainty space. The sampling of the input space was performed with Latin hypercube sampling (LHS). LHS is an efficient and proven method, able to produce more stable results than for instance random sampling [34]. The approach of this analysis was based on the work by Sin and Gernaey [35]. The quantification and representation of the input uncertainty is shown in Table 2. In addition to these values, the available excess heat, operating hours and temperature (in degree Celsius) were described with an uncertainty of ± 15 % with uniform distribution. In this work, the mean and standard deviation were reported for the results.

In order to identify the most important model input parameters, Morris Screening [36] was used in this work for the sensitivity analysis. This method estimates the Elementary Effects (EE) for all uncertain input parameters on the model output. First samples were created using the Morris sampling, followed by the model evaluations. The EE were then determined for each input and the input parameters were ranked according to their mean and standard deviation. The Morris screening has further three degree of freedom, which have to be chosen: the number of levels p, the number of repetitions r and the perturbation factor [37]. After evaluating different settings, the reported screenings was chosen to be 20 repetitions and 6 levels, which results in a perturbation factor of 0.6.

3. Results

3.1. Geographical Mapping

Fig. 2 shows Denmark with the individual excess heat sources marked as a point layer and the sum of the excess heat in each Danish district. An overview of the data used can be obtained from this figure. It can be further seen that the highest excess heat potentials are found in Aalborg, Kalundborg and Fredericia, where heavy industry is located. The greater Copenhagen area, with a high density of sources, has however a comparable low excess heat potential as there is no heavy industry such as oil refineries and building material production.

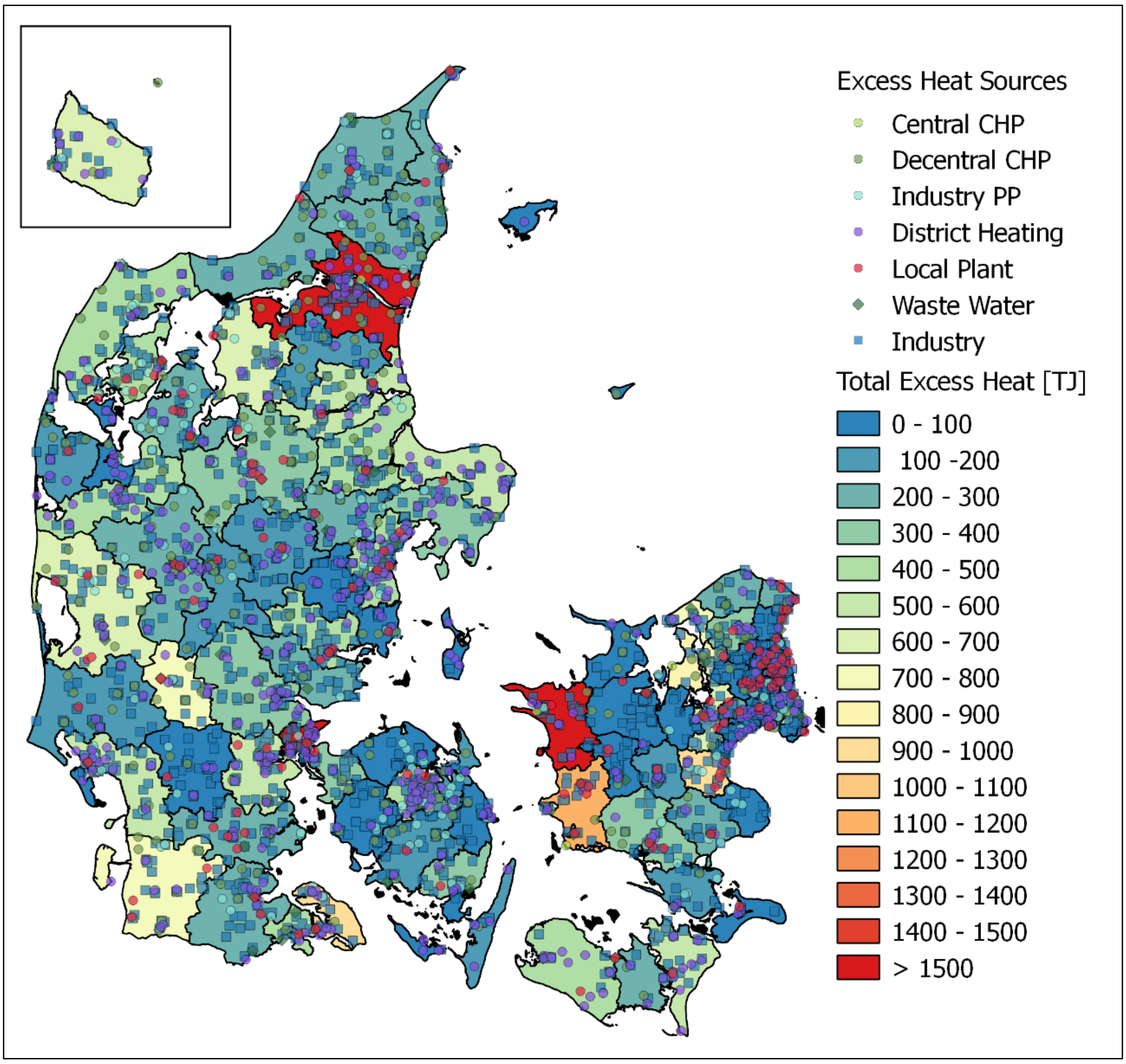

Fig. 2. Map of Denmark with the location and type of the excess heat sources and the total sum of excess heat of each region.

3.2. Excess Heat and Heating Demand

In Fig. 3 the excess heat considered in this work is shown by temperature level and from which sector it originates [15]. In addition the thermal process heating demand in the industry is shown for the five most relevant sectors [14]. As can be seen in the figure, the majority of the excess heat originates from the utility sector, in particular from power and waste water treatment (WWT) plants. The high temperature excess heat from the power plant might not be accessible to a large degree. From the industry sector, large excess heat amounts are in the range from 30 °C to 50 °C, being primarily useable through heat pumps. The food, petrochemical and chemical industry present the highest excess heat in this range. High temperature excess heat above 150 °C is to a small degree available from the food, pulp & paper and chemical industry, originating primarily from exhaust gases of boilers. The building material and metal industry emit together more than 425 TJ of high temperature excess heat, potentially useable through direct heat transfer or for conversion to power. From Fig. 4 the heating demand of the major industrial sectors can be seen, which is potentially coverable by direct heat exchange or heat pumping using excess heat as a source. The highest potential is found between 80 °C and 100 °C, required mainly in food, chemical, building material and pulp and paper industry.

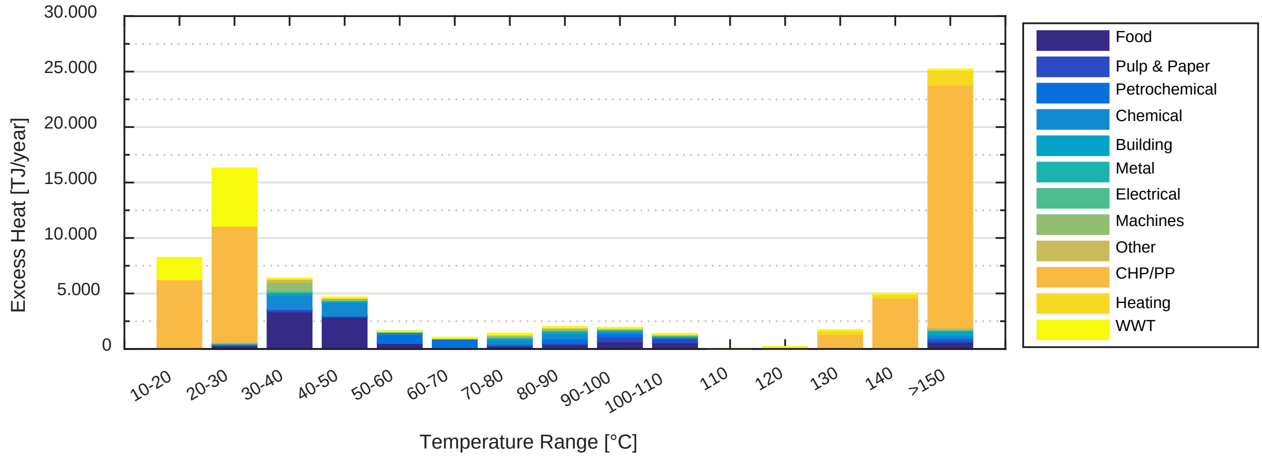

Fig. 3. Industrial excess heat in Denmark and its distribution across temperature ranges and sectors in Denmark based on data from [15].

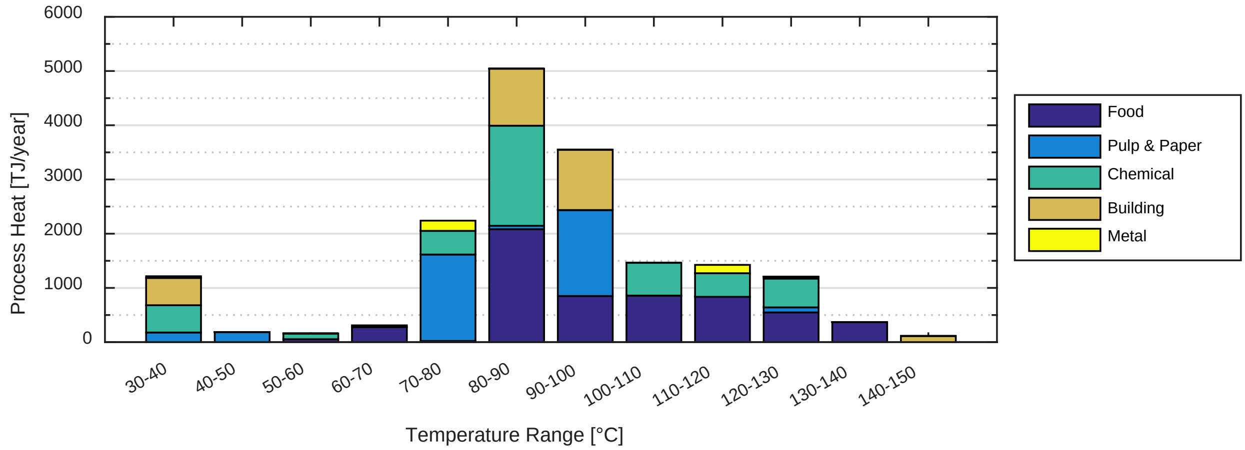

Fig. 4. Industrial process heat demand below 150 °C and its distribution across the industry and temperature ranges in Denmark based on data from [14].

3.3. Identification and Analysis of Recovery Scenarios

Based on the overall mapping as shown in section 3.1, several potential cases were identified, which are used in the following for further investigation. Fig. 5 shows the excess heat sources and district heating areas for selected areas where the utilisation is expected to be feasible. Case 1 shows a large excess heat source, originating from the chemical industry, near a district heating area. Case 2 shows an excess heat source, originating from the metal industry, within a district heating area. Case 3 shows two large excess heat sources, one from the food industry and one from waste water treatment, close to each other without a nearby district heating plant. Lastly, case 4 shows several large excess heat sources, from the building material industry without a nearby heating area.

In the following, each study is analysed with respect to the characteristics of the excess heat source and heating demand, as well as the economic potential for utilising the excess heat.

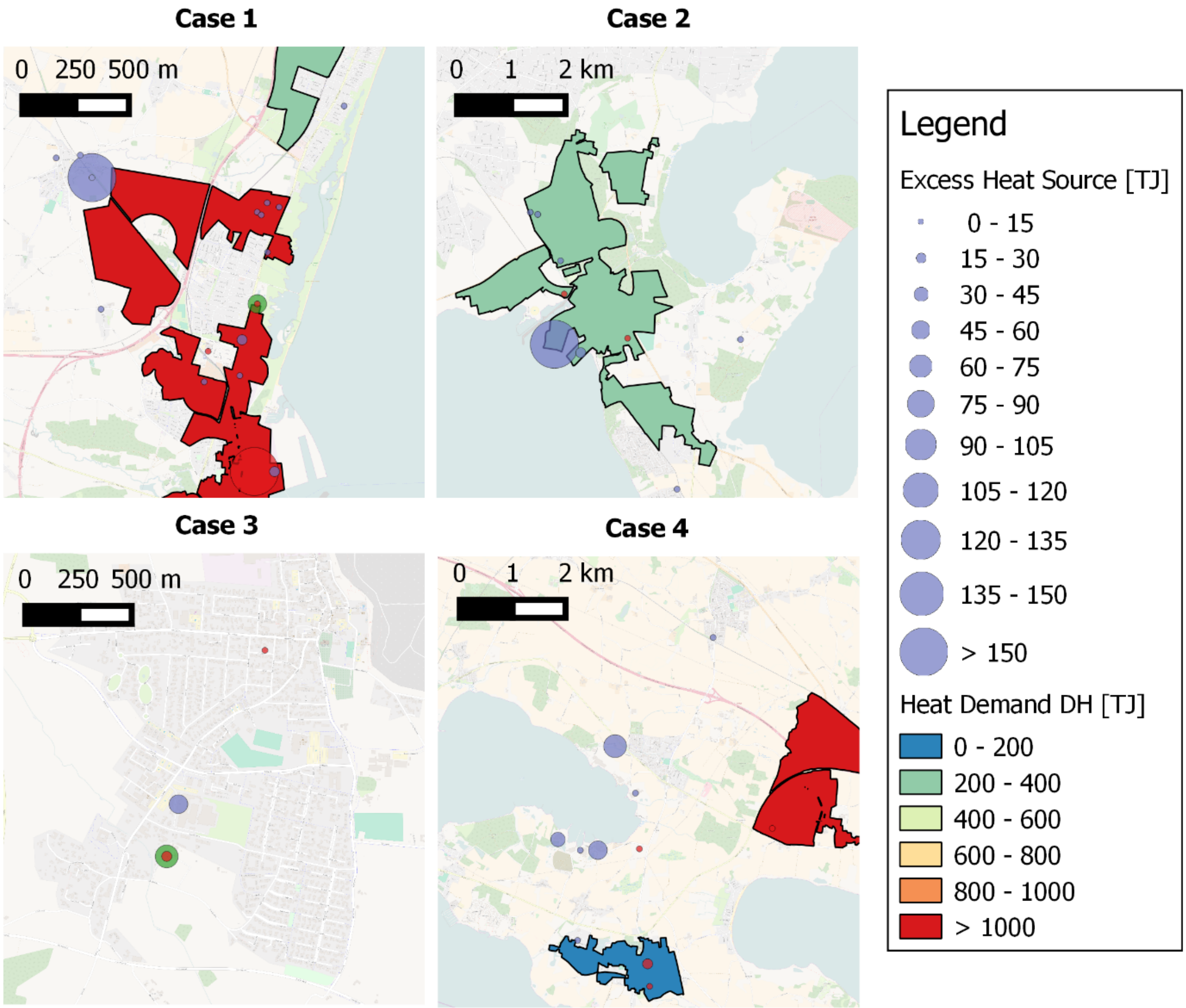

Fig. 5. Examples of the identified case studies based on the overall mapping. The maps show excess heat sources as points with the radius of the points proportional to the annual excess heat. District heating areas are marked as polygons with the colour representing the annual heating demand.

3.3.1. Case Study 1

In the first case study, the supply of excess heat to a district heating network was analysed, where the temperature level of the excess heat does not allow a direct heat exchange and thus a heat pump is required. The heat source considered was a chemical plant, located in Køge, where excess heat is available from evaporation, compression and refrigeration [15]. Temperatures of these processes are relatively low, in the range of 40 °C to 100 °C. For the specific case study an overall excess heat potential of 150,000 GJ per year was found for the source based on the mapping. A detailed analysis of the source revealed that approximately 10,000 GJ were available at 80 °C from one distillation column on site. Furthermore the production has 3 shifts and was considered evenly distributed throughout the year (P1). The heating demand of the local district heating system is more than 9,670 TJ per year with a supply temperature of 90°C. A major part of this heat is supplied by central combined heat and power plants, of which 400 MW are from three politically prioritised waste incineration plants [38]. The choice of the district heating profile depends on the agreement found with the local authorities and how much of the existing summer capacity could be reduced. As the estimated excess heat source is small, compared to the total network capacity, the first district heating profile was chosen.

3.3.2. Case Study 2

The second case study analysed the supply of excess heat to a district heating network, where the temperature level of the excess heat is sufficient to allow a direct heat exchange. In the specific case, a metal processing industry, located in Frederikssund, was chosen, which lies within an existing district heating network. In this industry the majority of the excess heat originates from heating, melting and compression. Also here more than 150,000 GJ of excess heat are available a year, as estimated in the current mapping. The specific site manufactures steel plates, where a high share of thermal energy is used for the heating of the metal, before being formed. It is assumed that 15,000 GJ (10 % of total) are accessible at a temperature of 180°C. The local district heating network has a heating demand of 397 TJ per year and, in winter, has a supply temperature of 80°C. The steel plates are produced in three shifts and, to account for demand fluctuations, production profile P2 was chosen. Based on the production profile and the corresponding demand, a total of 11.36 TJ of excess heat was found to be supplied to the district heating network.

3.3.3. Case Study 3

The use of industrial excess heat within the industry itself is analysed as part of the third case study. Here the industrial excess heat can be used as process heat, either through a heat pump or direct heat exchange. A possible scenario was found in the mapping, where up to 50 TJ of excess heat is available from the food industry and around 65 TJ from a waste water treatment plant, which is coupled to a local combined heat and power plant with a capacity of approximately 0.5 MW_e and 10 MW_{th}. As there was no existing larger district heating network found in this area of Faxe, the heat could be used for local industries.

The site for the food production has an estimated heating demand of 20 TJ in the temperature range of 80°C for heating and cooking, following a two shift operation and production profile P1. The excess heat from the WWT plant was found to be at 110°C based on the GIS model with an accessible potential of 15 TJ per year.

3.3.4. Case Study 4

The use of industrial excess heat in cases where no heat demand is available and excess heat temperature are high enough to generate electricity is considered in the fourth case study. The mapping identified an area west of Sønderborg, where several industries producing building material are located. These industries are not in the vicinity of other major heating demands, such as the district heating areas of Sønderborg and Broager. The main products of the industrial sites are bricks and the estimated excess heat from those was estimated to be 62 TJ, 56 TJ, 36 TJ and 12 TJ per year, respectively. As those industrial sites will have similar processes, with comparable process heating demand, the exchange of heat between them is not possible. Furthermore the closest district heating area is located more than 3 km away. In the production of bricks the majority of excess heat originates from drying and furnaces. The exhaust gases in the brick production are typically found to range between 50°C and 80°C from the dryers and between 150 °C and 250°C for the furnace [39,40]. Already installed heat recovery systems and the use of the kiln flue gases for the dryer, reduce possible process stream for further utilisation. The temperature of the furnace air was chosen at the lower end as 160°C and the useable excess heat amount at 30 TJ. Connecting the industrial site to the district heating area would result in TCI of more than 750,000 €, resulting in a simple payback time of the project above 9 years and an IRR of 11 %. It was thus considered that the excess heat from the furnace was able to produce electricity with an ORC, as a better economic performance was found as can be seen in Table 5.

3.3.5. Economic Analysis

The results of the evaluation of the case studies are summarised in Table 4 and 5. The unit costs found in the case studies can be compared to the current costs of the system. Case 1 presents the highest investment costs, while generating only slightly more heat than case 2, due to the required heat pump. This is also shown in the unit costs, which are with 35.68 € per MWh considerably higher for case 1 but still less than substitution price. However, a relatively high internal rate of return is obtained for all cases, which is considerable above the discount rate and high compared to the simple payback time. The simple payback time can thus only be used in combination with the other indicators. All cases are economically feasible, with standard deviations below ± 25 % for unit cost and IRR, except case 3. In that specific case, the reason for the increased uncertainty is that the uncertainty of the excess heat temperature of the gaseous source in some uncertainty estimation causes the use of a heat pump, which has a great impact on the heat delivered, investment costs and operating costs. This was also shown in the sensitivity analysis, where the excess heat temperature for case 3 has an over proportional influence. Despite having high investment costs, the ORC system in case 4 results in a high NPV of 440 thousand Euro.

Table 4. Summary of the excess heat potential of the case studies and of the mean and standard deviation of the recovered energy and investment costs.

	Total EH [GJ year $^{-1}$]	Useable EH [GJ year $^{-1}$]	T_{EH} [°C]	Product [year $^{-1}$]		TCI [€ 10^3]	
Case 1	> 150,000	10,000	80	11,700 GJ_{th}	± 9 %	320	± 15 %
Case 2	> 150,000	15,000	180	11,300 GJ_{th}	± 9 %	68	± 13 %
Case 3	115,000	15,000	110	8,600 GJ_{th}	± 43 %	192	± 121 %
Case 4	62,000	30,000	160	3,270 GJ_e	± 12 %	194	± 17 %

Table 5. Summary of the economic results for the case studies, showing the mean values and relative standard deviation of the Monte Carlo simulations.

	Unit Costs [€ MWh^{-1}]		Max. Invest. [€ kW^{-1}]		IRR [%]		NPV [€ 10^3]		Simple Payback [years]	
Case 1	35.81	± 10 %	997	± 9 %	14	± 22 %	291	± 41 %	10.9	± 30 %
Case 2	1.74	± 13 %	1,178	± 9 %	48	± 14 %	511	± 11 %	2.2	± 14 %
Case 3	4.86	± 79 %	734	± 9 %	24	± 41 %	202	± 65 %	6.4	± 83 %
Case 4	16.74	± 14 %	1,230	± 11 %	20	± 18 %	440	± 26 %	6.1	± 20 %

The results of the sensitivity analysis, with the most influential model parameters, are shown graphically in Fig. 6 for the Unit costs. The lines in each graph represent the mean value ± the standard deviation divided by square root of the repetitions [41]. Points lying outside of the lines have significant impact on the output. If the points are to the right of the curve, they have a positive impact on the results and vice versa. Parameters with a high absolute mean value have a high significance for the model, whereas a high standard deviation represents high interactions of the parameter. For case 1 the parameters with the highest influence were the costs related to electricity, as well as the parameters influencing the performance of the heat pump. On the contrary, case 2 where the excess heat is used directly, has a high sensitivity to the costs of piping and the excess heat characteristics. The highest uncertainty was found for case 3, where the excess heat temperature has a very high influence, as it determines whether or not a heat pump has to be used. Consequently also the minimum temperature difference and heat pump costs have a high impact. For the ORC case, the main influential factors were the annual operating hours and costs directly related to the ORC investment, however their impact on the standard deviations were comparable low to the other cases. However, the obtainable subsidies have a small impact on the results.

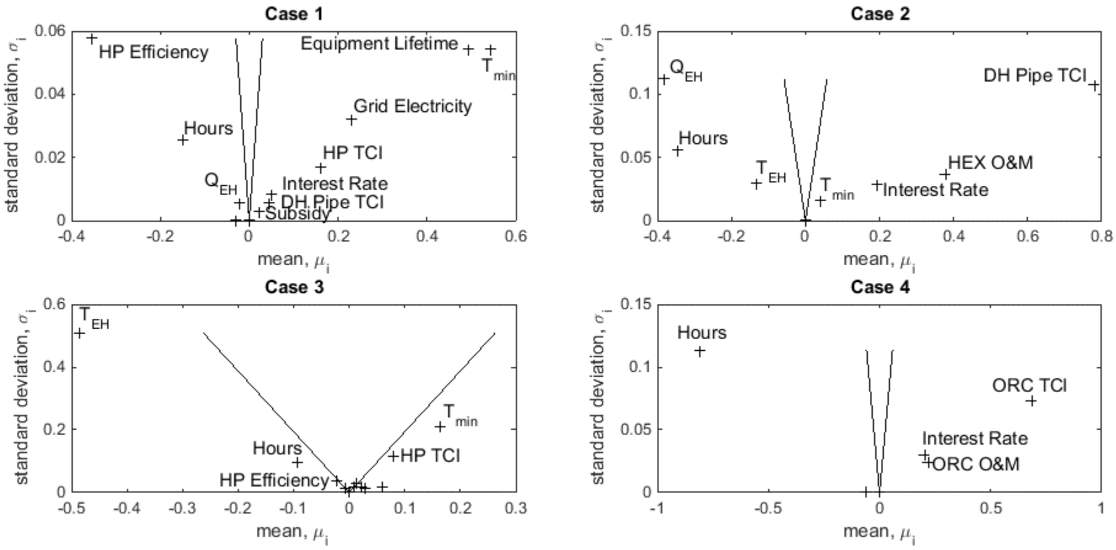

Fig. 6. Results of the sensitivity analysis for the unit costs using Morris Screening for each case study.

3.3.6. Environmental Considerations

The data implemented in the GIS model further allows an evaluation of potential conflicts with current heat producers and environmental benefits. An example of the possibilities is given in the following for the first two cases.

The proposed match in case 1 would supply heat to one of Denmark's largest district heating networks. Currently the network is supplied by heat from several central combined heat and power plants, which are using biomass (wood chips and pellets) or are in the transition of replacing coal with biomass. The delivered district heat from the chemical plant was found to decrease the heat supply from existing sources by less than 0.2 %, having negligible influence on the power production.

For case study 2, the current district heating demand was covered by 84 % of wood chips, 13 % natural gas and 3 % bio oil fired in one heating plant. Substituting some of these fuels would thus not impact electricity production. Carbon emissions would not be reduced significantly as the majority of the district heat is supplied from biomass and the excess heat originates from burned natural gas.

4. Discussion

The excess heat used for the geographical mapping takes into account more than 2500 industrial sites and groups of excess heat from different sources and sites. The excess heat found for a given point may thus originate from multiple sources. It is thus necessary to carefully analyse any match and the near vicinity of the point sources to determine the real potential of excess heat and heating demand for any match. Information from the literature can be used in a first estimate to describe the excess heat sources. It should further be carefully evaluated if there are any opportunities for heat integration on site or reduction of the excess heat by improved equipment and process control, as this would be favoured to an external utilisation. Replacing for instance a boiler generating useable excess heat, with a more efficient one, could be more favourable.

The economic analysis used general numbers to describe the costs of the given system, without doing a detailed technical evaluation of component sizes. However, the economic evaluation was performed to give a quick overview of the feasibility of a found match and should be able to be applied to a large number of cases without having to specify additional parameters than the ones found in the geographical mapping or literature. If a match is assessed as feasible with the given uncertainties, a more detailed evaluation has to be undertaken. This evaluation should also include the necessity of using thermal storage tanks to account for daily load and demand variations, a detailed analysis of the processes on site and how the excess heat can be utilised. The sensitivity analysis shows further the most important parameters, for which the quantification should be made with care. These are, besides the investment costs and heat pump efficiency, the annual operating hours, accessible excess heat amount and temperature. The substitution price depends on the local energy network and, together with the agreements between the owner of the excess heat and the utility company, has an impact on the final economic outcome. The model developed in this work can help both parties to assess the profitability in the first negotiating round and various stakeholders and decision makers in identifying national and regional potentials.

5. Conclusion

This work presents the results of a geographical mapping in GIS of excess heat sources from the industry and utility sector in Denmark. The mapping was used to show its potential for identifying specific cases where excess heat can be utilised externally for heating purposes or electricity production. A model for a fast economic and technical evaluation of potential matches was developed, integrating excess heat sources and heat demands, which is relevant to screen matches before a detailed analyses.

The results showed, that the GIS model in combination with economic and technical analysis was suitable to identify cases where excess heat can be utilised. This has a particular interest for regional energy planners. The evaluation of the chosen cases further shows, that the utilisation of excess heat was feasible for different characteristics of the sources and sinks. In all cases, the heat or electricity would be supplied below the current substitution prices for district heat and electricity. The reported standard deviations of the mean, found with the Monte Carlo method, shows an acceptable uncertainty in most cases. When the estimated excess heat temperature was close to the required sink temperature, the uncertainty increases, as the use of a heat pump might be required with corresponding increases in cost.

Nomenclature

a	shape parameter [-]	Q	heat flow [TJ]
b	inverse scale parameter [-]	r	repetitions [-]
p	perturbation [-]	T	temperature [°C]

Greek Symbols

Δ	absolute difference [-]	μ	mean [-]
η	efficiency [-]	σ	standard deviation [-]

Subscripts and superscripts

0	reference point, Ambient	min	minimum
EH	Excess Heat	S	Supply
el	electric		

Abbreviations

AF	Annuity Factor	N	Normal
COP	Coefficient of Performance	NPV	Net Present Value
DH	District Heating	O&M	Operation and Maintenance
EE	Elementary Effects	ORC	Organic Rankine Cycle
G	Gamma	P	Production Profile
GIS	Geographical Information Systems	TCI	Total Capital Investment
HP	Heat Pump	U	Uniform
IRR	Latin Hypercube Sampling	WWT	Waste Water Treatment
MC	Monte Carlo		

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